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A STUDY OF SOME EXAMPLES OF ROCK VARIATION.[1]

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In the following article I purpose to describe briefly a series of igneous rocks which vary from those of acid character through those of intermediate and basic characters to others which are ultrabasic in composition. The rocks occur upon the upper peninsula of Michigan, in the vicinity of Crystal Falls, the most important town in the iron-bearing district of the same name. All are to be found in an area extending from Crystal Falls southeast to a mile east of the Michigamme River. In the description of the various kinds no detailed mention of localities will be given, since they are given in the complete article, and if wanted can readily be found by reference to it. The rocks occur as knobs or groups of knobs, and as well determinable dikes cutting the knobs. The outcrops project through an area covered by glacial deposits. The best exposures are naturally near the river, where erosion has removed the drift mantle.

Here and there in the drift are isolated exposures of sedimentary rocks of Upper Huronian age. The relations of the igneous rocks to the sedimentaries are not shown by exposures of direct contacts, but it is inferred from the occurrence of sedimentaries between the igneous exposures that the drift is underlain by Upper Huronian sedimentaries, and that the igneous rocks are intrusive in them. The intrusives have never been found to penetrate the superimposed, horizontal, Lake Superior, Potsdam sandstone. These facts are conclusive proof that their period of intrusion fell in the time between the deposits of the Upper Huronian and those of the Cambrian. In the complete article there is a discussion of the time of the folding of the Upper Huronian, and the conclusion is reached that this folding took place immediately preceding the deposit of the Keweenawan series. If these intrusives had existed at that time, they must certainly have suffered from the orogenic movements. Examination of the exposures of the intrusives has not shown schistose masses, nor has detailed microscopical study disclosed any textures which accompany powerful dynamic movements, except in isolated cases which are presumed to be due to purely local movements. Such being the case, the conclusion follows that these intrusives are subsequent in their origin to the folding of the Upper Huronian; that is, are of Keweenawan or of post-Keweenawan age.

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[1] This article is a brief abstract of a part of a report which will appear in full as a monograph of the U. S. Geol. Surv., under the title of "The Crystal Falls Iron-bearing District of Michigan." For details which are not warranted in this place the reader is referred to the monograph. An abstract of the monograph, in which the portion treated in the present article is barely mentioned on account of lack of space, will be published under the same title as the monograph in the 19th Annual Report.

It seems highly probable, though it cannot now be proven, that the intrusives are contemporaneous with the period of volcanic activity, during which the heterogenous Keweenawan series was formed. During the formation of such a great series we might well expect more or less fissuring of the sedimentaries and intrusion of molten magma in a district no farther removed from the scene of eruptive activity than is the Crystal Falls district from the Keweenawan, a distance of about thirty miles. It is at least clear that the rocks are post-Huronian and pre-Potsdam, but a closer approximation cannot be made with certainty.

With few exceptions the intrusive rocks are medium to coarse-grained. While the granitic texture is unquestionably predominant, other textures are not absent, for we find some ophitic and porphyritic textured rocks, and others in which even a parallel (flow) texture has been produced. It has already been intimated that the chemical range is very great. There is, of course, a corresponding range in color.

The main classes with which the variations will be grouped are the diorites, the gabbros, or gabbro-norites, and the peridotites. Complete and accurate chemical analyses of certain rocks of these chief classes have been obtained and the microscopical diagnosis thereby confirmed. Within each of these main divisions well marked varieties can be distinguished. While between the gabbros and the peridotites a transition is unquestionable, a less positive statement must be made for the connection between the diorites and the gabbros, and while the writer is convinced that such connection exists, he is aware that the reader may not take the same position. In the following pages the three main classes will be briefly described, and then the variations within each class. The relations between the various main divisions will be described, and then, with a brief summary of the facts, the reader will be enabled to draw his own conclusions.

Diorites.—Following Brögger's definition,[1] the name diorite is in the following pages restricted to granitic textured plutonic rocks of intermediate acidity, consisting essentially of plagioclase and either primary hornblende, pyroxene, or mica, or two or more of these.

This is very different from the usage by a number of the previous writers on the Lake Superior region, who called the uralitized dolerites "diorites" or "epidiorites." As a result of the introduction of the use of this name diorite by scientific men, it is now in common use among the miners in the Lake Superior iron regions, and is usually applied by them to any greenish rock whose sedimentary characters are not clearly recognized, very much in the same way that the field geologist uses greenstone, especially if the green rock is associated with an iron formation. In the great majority of cases such rocks are dolerites in a more or less advanced stage of alteration, and rarely, if at all, pure diorites.

The dioritic rocks are of medium to coarse grain. In texture they show some variations from rocks of a granitic texture to others which incline to the ophitic texture, and to still others which are distinctly micropegmatitic. The granitic texture is the most frequent. The color is uniformly light gray or reddish, but at times, when the ferromagnesian minerals are present in greater quantity, they become dark gray or greenish brown.

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[1] Die Eruptivgesteine des Kristianiagebietes, by W. C. Brögger in Videnskabsselskabets Skrifter, I Mathematisk- naturv. Klasse. Pt. I, Die Gesteine der Grorudit-Tinguait-Serie, 1894, No. 4, p. 93. Pt. II, Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol, 1895, No. 7, p. 35.

The important mineral constituents are feldspar, quartz, hornblende, and biotite. Apatite, zircon, sphene, iron oxide, and epidote (?) are the accessory minerals. The secondary minerals present are white and brown mica, chlorite, epidote, zoisite, calcite, and rutile. Plagioclase feldspar, orthoclase, and microcline occur together. The plagioclase is present in individuals which are fairly automorphic. In the ophitic textured diorites, the plagioclase is the best developed of any of the essential constituents. In the granitic textured rocks the degree of automorphism is highest where orthoclase and quartz are present in the largest quantity, and diminish as these diminish in consequence of the interference of the plagioclase individuals. For the most part the plagioclases yield rather narrow sections, though they can hardly be called lath-shaped. Measurements show the plagioclase to be andesine. It is very much altered. Orthoclase is present in large plates, which form a part of the mesostasis for the plagioclase and the bisilicates. The quantity of orthoclase varies considerably. It is very much decomposed. Microcline is not abundant. It is very fresh, and in many cases automorphic with respect to the orthoclase and quartz. Quartz is present in variable quantity, and with the orthoclase forms the mesostasis. The hornblende shows a good development in the prismatic zone. The terminal planes are not so well developed. It varies from dirty green to reddish-brown in color. The reddish-brown variety occurs in the center of the crystals and is surrounded by the green. The differently colored zones thus produced are not sharply delimited, and are also in perfect optical continuity. No evidence is found indicating the green kind to be an alteration product from the brown variety, and they are both assumed to be primary. The biotite is brown, and shows its usual characters. It is less well developed than the hornblende. All of the other minerals show their usual well-known characters.

According to the variations in the proportions of the essential minerals, plagioclase, orthoclase, quartz, hornblende, and biotite, we get the following varieties of diorite : quartz-diorite, tonalite, quartz-mica-diorite, and mica-diorite. This variation is best shown in a connected group of knobs composed of medium grained rock, which varies in color from light pink to a very dark greenish-gray. Areas of light and dark colored rock may be seen extending in finger-like projections into one another. There are no sharp boundaries between them, however, but, on the contrary, a gradual passage from the light to the dark variety. Some of the rocks also contain small, more or less rounded areas, which are clearly segregations of ferromagnesian minerals. These different phases evidently belong to a single rock mass, but the microscope enables a separation to be made into the several mineralogical and textural facies already mentioned. The main mass of the rock forming the knobs appears to be a tonalite which resembles the published description by Becke[1] of that from the Rieserferner. It also closely resembles some slides of the typical Adamello tonalite with which I have been able to compare it. This tonalite grades by diminution of biotite with corresponding increase of hornblende into quartz-diorite, and by a diminution or disappearance of the hornblende and increase of the biotite into a quartz-mica-diorite. Where the quartz of this last variety is practically wanting, we get a mica-diorite. In this small massif pure types of the rocks described are of rare occurrence. Orthoclase is present in all of these dioritic rocks. In certain facies the orthoclase and quartz are very abundant, and the plagioclase correspondingly subordinate. Such rocks approach closely the plagioclase-bearing granites.

The relationship to granites is better shown in a different occurrence from the one just described, in which the greater portion of the rock is a plagioclase-bearing biotite-granite, showing in many cases most beautiful micropegmatitic texture, but with schlieren of a darker colored rock which might readily be called a quartz-mica-diorite. It is especially interesting to note also that this series of exposures is cut by a number of small dikes of uniform character, varying from fractions of an inch to three inches in width. The dike rock is very light gray to pink in color, and cryptocrystalline. Examined under the microscope, these dikes can be readily separated into a microporphyritic center, and a micrgroganitic textured selvage. Phenocrysts of quartz, feldspar, and biotite lie in a microgranitic groundmass of feldspar and quartz, between which occur secondary flakes of muscovite. The rock is a microporphyritic quartz-mica-diorite or quartz-mica-diorite-porphyry. This rock seems to bear a very strong resemblance to the tonalite-porphyrite described by Becke[1] which occurs as a dike facies of the Rieserferner tonalite to which I have already referred.

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[1] Petrographische Studien am Tonalit der Rieserferner, by F. BECKE, Tsch. Mitt. Vol. XIII, 1892, pp. 379–464.

Still another illustration of the passage from the granitic to the dioritic rocks was observed upon a dike, four feet wide, which penetrates a knob of hornblende-gabbro. A specimen taken near the center of the dike discloses itself as a biotite-granite with a small amount of plagioclase. The sides of the dike consist of diorite, composed of andesine feldspar, and biotite, without any quartz. The sharp line of demarkation which exists between the dike and the gabbro seems to preclude the possibility of a fusion and mingling of the two rocks, such as has been suggested by Johnston-Lavis,[2] as in some cases causing variation in chemical composition of intrusive rocks, especially where this variation is one between the center and periphery of an intrusive mass. The diorite occurrences of the Crystal Falls district seem, in the gradations mentioned, to be very similar to the tonalite from the Rieserferner described by Becke,[1] and also to the so-called grano-diorite massifs of California, described by Becker, Turner,[2] and Lindgren.[3] The grano-diorite of California appears from Lindgren's description to correspond very closely to tonalite, though Turner uses the name as synonymous with quartz-mica-diorite.

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[1] Loc. cit., pp. 434–441.

[2] The causes of variation in the composition of igneous rocks, by H. J. JOHNSTON-LAVIS: Natural Science, No. 4, pp. 134–146.

The basic eruptive rocks of Gran, Norway, and their interpretation, by H. J. JOHNSTON-LAVIS: Geol. Mag., 4th decade, Vol. I, 1894, p. 252.

It has not been found possible thus far to obtain analyses of all these varieties. The more acid facies of the diorites seem to show very clearly their gradation towards tonalites and granites, and, from their content of free silica, the conclusion seems to be warranted that they are rather acid. Such being the case, it was deemed of more importance to study the relations of the less acid dioritic facies in order to determine their relationship with the basic gabbros and peridotites with which their connection is not so evident as it is with the granites. To this end a complete analysis was made by Dr. H. N. Stokes of a mica-diorite. The rock analyzed consists of biotite, hornblende, plagioclase, orthoclase, and quartz, with the biotite and plagioclase as the predominant characteristic constituents.

ANALYSIS OF MICA-DIORITE BY DR. N. H. STOKES.

SiO_2	58.51	MgO	3.73
TiO_2	.72	K_2O	4.08
Al_2O_3	16.32	Na_2O	3.11
Cr_2O_3	none	H_2O at 110°	.23
Fe_2O_3	2.11	H_2O above 110°	2.00
FeO	4.43	P_2O_5	.30
MnO	trace	CO_2	none
NiO	none		
CaO	3.92		99.46

Gabbros and norites.—The gabbros and norites are holocrystalline rocks of moderately fine to coarse grain. The rocks here included show a considerable variation in texture. Some of the finest grained forms possess a very good parallel texture. Others are noticeably porphyritic. A few have a poikilitic texture. Less common is an approach to the ophitic texture of the dolerites. Most commonly of all, however, the rocks are granitic in texture. The color variation is not great, and is chiefly in dark brown or greenish-black tones. The important mineral constituents are feldspar, biotite, hornblende, pyroxene, and olivine. Apatite, sphene, zircon, rutile, octahedrite, brookite (?), and iron oxide occur as accessory minerals. White and brown mica, chlorite, hornblende, talc, serpentine, sphene, rutile, and calcite occur as secondary minerals.

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[1] Op. cit.

[2] Geology of the Sierra Nevada, by H. W. TURNER: 17th Ann. Rep. U. S. Geol. Surv., No. 1, 1896, pp. 636–724.

[3] Granitic rocks of California, by W. LINDGREN: Am. Jour. Sci., 4th series, Vol. III, 1897, p. 308. Here can be found reference to earlier articles on grano-diorites.

Plagioclase and orthoclase-feldspar are both present. The last is, however, of doubtful occurrence. The plagioclase is labradorite, and shows its usual characters.

Hornblende is the most striking component in the majority of the sections. It is present in three different varieties, all of which occur in anhedra. The most prominent kind is a reddish-brown hornblende, which has a dark green hornblende commonly associated with it, and frequently in zonal intergrowth with it. This hornblende occurs without the green kind, but the green is invariably associated with the brown variety. The two are optically continuous in the intergrowth. It is possible, though not susceptible of proof, in the sections examined, that the green hornblende is the incipient alteration of the brown hornblende. The pleochroism is strong in the following colors:

Brown hornblende.

a	**b**	**c**
Light yellow or red, with tinge of green.	Reddish-brown.	Same as **b**, or else a darker reddish-brown. Exceptionally it is a light yellowish-brown.
		c> b>>a

Green hornblende.

a	**b**	**c**
Greenish-yellow.	Yellowish or brownish-green.	Darker olive-green. Frequently with bluish tinge.
		c>b>a

This hornblende, with respect to its rather exceptional pleochroism and its general characters, seems to agree very well with that described by van Horn[1] from very similar rocks from Italy, and like that is possibly very basic. The brown hornblende possesses a further interest in that it is frequently rendered very dark by the number of exceedingly small inclusions within it, and in this, and also in its color, resembles so strongly hypersthene as to be readily mistaken for it upon cursory examination. The inclusions referred to are determined to consist of characteristic heart-shaped and geniculate twins of rutile, and pointed pyramidal crystals of octahedrite. Others show a flat tabular development, somewhat similar to that of brookite, though these could not be positively determined as that mineral. Associated with the above were numbers of hexagonal, clove-brown plates appearing in cross section as sharp lines. A gradation between these plates and large masses of ilmenite was traced. It thus appears that these inclusions are all titaniferous minerals.

The second kind of hornblende is the compact, strongly pleochroic common green hornblende, and the third kind is a non-compact reedy variety of light green hornblende. This last is probably secondary, but secondary after the original hornblende, thus not affecting essentially the character of the rock.

The pyroxene is represented by a monoclinic variety and by the orthorhombic bronzite. The presence of olivine was determined with considerable doubt. None of the remaining minerals show anything of special interest.

The leading essential constituents described are combined in variable quantities, and accordingly a number of different mineralogical types of rocks are produced. The important types which will be described are hornblende-gabbro, consisting essentially of hornblende and labradorite; gabbro, consisting of monoclinic pyroxene and labradorite; and bronzite-norite, composed of bronzite and labradorite. These various mineralogical types exhibit very interesting ranges in texture, to which attention will be called. The hornblende-gabbro of granitic texture is the prevailing rock. An analysis of such a rock shows the following composition:

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[1] Petrographische Untersuchungen über die Noritischen Gesteine der Umgegend von Ivrea in Oberitalien, by F. R. VAN HORN. Tsch. Mitt., V Heft, 17 Bd., 1897, p. 409.

ANALYSIS OF HORNBLENDE-GABBRO BY MR. GEORGE STEIGER.

SiO_2	49.80	Na_2O	2.22
TiO_2	.79	H_2O 100°−	.13
Al_2O_3	19.96	H_2O 100°+	1.71
Fe_2O_3	6.32	P_2O_5	.07
FeO	.49	CO_2	.15
CaO	11.33		
MgO	7.05		100.63
K_2O	.61		

In one of the hornblende gabbros a porphyritic texture is very pronounced. Porphyritic brown hornblendes, which are poikilitic from inclusions of feldspar and a few grains of augite, lie in an imperfectly ophitic groundmass. This rock grades into a finer grained nonporphyritic granitic textured gabbro. Both mineralogical and textural variations are well shown in another occurrence, in which the relations of the respective varieties are clearly seen. The normal granitic hornblende-gabbro is cut by numerous narrow bifurcating dikes, which are very dark, of fine grain, and stand out clearly from the main mass of the coarse-grained gabbro. These dikes contain a larger percentage of biotite than is found in the normal gabbro, but most interesting is the presence along the sides of the dikes of a well-marked parallel arrangement of the minerals. This is presumed to be a true flow structure consequent upon the flowage of the magma, where it was forced in the fissures, as none of the minerals bear indications of secondary origin, and show but faint evidence of the effects of pressure.

These dikes, as well as the main mass, are cut by a coarse-grained bronzite-norite. Bronzite, hornblende, and labradorite are the essential constituents of this rock, arranged in order of their importance. The following analysis gives its chemical composition:

ANALYSIS OF BRONZITE-NORITE BY MR. GEORGE STEIGER.

SiO_2	48.17	Na_2O	1.34
TiO_2	1.00	H_2O { 100°−	.19
Al_2O_3	25.26	100°+	2.00
Fe_2O_3	1.13	P_2O_5	.07
FeO	6.10	CO_2	.43
CaO	9.53		
MgO	4.22		100.17
K_2O	.73	MnO, etc., not looked for.	

The last gabbro occurrence to be mentioned is one in which we find the normal type of hornblende-gabbro cut by a dike in which monoclinic pyroxene is in about equal quantity with the hornblende. This evidently represents a transition towards a true gabbro. This exposure of gabbro is cut by a peridotite, which is feldspathic and concerning which detailed statement will be made in the following pages.

The rocks just described may be compared in their variation to those described by G. H. Williams[1] from Maryland, by Chester[2] from Delaware, and by Fairbanks[3] from California. A series of basic rocks similar in many respects to those of Crystal Falls has also been described recently in two interesting papers by van Horn[4] and Schaefer.[5]

Peridotites.—The peridotites are all coarse-grained rocks of very dark color, consisting of the following chief mineral constituents: pyroxene (monoclinic and orthorhombic), olivine, hornblende, and biotite. Associated with them are feldspar, apatite, green and brown spinel, and iron oxide. The relative proportions of these minerals differs much, and yield different well-known rocks. The types are not sharply separated, but are found, both in the field and under the microscope, to grade into one another. The purest form of peridotite is the wehrlite, composed essentially of olivine and augite. Where, besides these minerals, hornblende is present in large quantities, the rocks belong to the amphibole peridotite type and approach Williams' cortlandtite. In some specimens the biotite is almost in sufficient abundance to warrant the naming of the rock biotite-peridotite. Again, feldspar is present in comparative abundance and the rock is a feldspathic wehrlite, and approaches an olivine-gabbro or an olivine-hornblende-gabbro.

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[1] The gabbros and associated hornblende rocks occurring near Baltimore, by G. H. WILLIAMS, Bull. U. S. Geol. Surv., No. 28, 1886. Outline of the geology of Maryland, Baltimore, 1893, p. 39.

[2] The gabbros and associated rocks in Delaware, by F. D. CHESTER, Bull. U. S. Geol. Surv., No. 59, 1890.

[3] The geology of Point Sal, by H. W. FAIRBANKS, Bull. Dept. of Geol., Univ. of Cal., Vol. II, No. 1, 1896, p. 56 et seq.

[4] Petrographische Untersuchungen über die noritischen Gesteine der Umgegend von Ivrea in Oberitalien, by F. R. VAN HORN, Tsch. Mitt, Vol. 17, 1897, pp. 391–420.

[5] Der basische Gesteinszug von Ivrea im Gebiet des Mastallone–Thales, by R. W. SCHAEFER, Tsch. Mitt., Vol. 17, 1898, pp. 495–517.

A number of exposures of the peridotites have been examined, but only one will be described here, and that has already been referred to under the gabbros. This peridotite cuts the gabbros. Sections made from different specimens taken from the exposure would be named, if considered separately, amphibole-peridotite, wehrlite, or even olivine-gabbro. This is the same exposure from which was taken a specimen described by Patton[1] as hornblende-picrite. In this rock there occur the following essential mineral constituents, given in order of crystallization: augite and olivine, apparently contemporaneous, orthorhombic pyroxene, hornblende, biotite and feldspar.

Of the mineral constituents forming the rock, augite is the only one which is automorphic, and then only when it is partially or wholly surrounded by feldspar. The olivine is in rounded individuals which are never associated with the augite in such a way as to enable their relative periods of crystallization to be determined. Orthorhombic pyroxene, apparently bronzite, occurs in grains inclosed in hornblende, and also forms a narrow zone around the olivine. The hornblende is predominately a brown variety, showing strong pleochroism ; **𝔞** is light cream yellow, **𝔠** is yellowish-brown, and **𝔟** is reddish-brown. **𝔟>𝔠>𝔞.** Patton[1] has already called attention to the exceptional pleochroism of this hornblende, in which the brownish color is that of rays vibrating parallel to the orthodiagonal axis. The brown hornblende is accompanied by a small quantity of green hornblende, which is in crystalline continuity with the brown, and is apparently original. The biotite began to crystallize before the hornblende had ceased growing, as we find it in ragged plates included by it, especially upon the periphery of the individuals. It is normally the least well-developed mineral present. Feldspar is present at times in small quantity, and forms the mesostasis. The olivine possesses a certain interest, as it is surrounded by zones[1] of different minerals; first, orthorhombic pyroxene, surrounded in its turn by green compact hornblende, which is in optical continuity with the predominant brown hornblende of the rock. This green hornblende lies next to the feldspar, and is traversed by anastomosing tabular feldspar growths.

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[1] Microscopical study of some Michigan rocks, by H. B. PATTON, in Sketch of the geology of the iron, gold, and copper districts of Michigan, by M. E. WADSWORTH, Rept. State Board Geol. Surv. for 1891, 1892, 1893, p. 186.

From the relations described as existing between the various minerals composing the peridotite, it seems that the following stages may be outlined in the progress of the consolidation of this rock: From the coarse, even-grained character, and from the fact that neither a fine-grained groundmass nor glass is present, the conclusion is warranted that it consolidated very slowly, and must have, of course, at some time been under very high temperature. The olivine and augite were the first of the chief silicate constituents to form, and crystallized out of the magma at approximately the same time. The magma soon reached a condition unfavorable for further production of olivine, probably on account of increasing acidity. There was then formed the orthorhombic pyroxene occurring in a zone surrounding the olivine. The monoclinic pyroxene continued to grow during the formation of this orthorhombic variety, as it is not surrounded by it. Finally, however, the condition of the magma was such that in the place of the monoclinic and orthorhombic pyroxene the crystallization of hornblende began.

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[1] Loc. cit., p. 186.

I do not know what the conditions were which caused the formation of the hornblende subsequent to and in such intimate association with the pyroxene, surrounding it in zonal growth. An explanation of such occurrences has been attempted by Becke[1] in a recent article in which the conclusion is reached that the formation of hornblende and pyroxene depends upon changes in temperature and pressure. His explanation is based upon the facts of occurrence of pyroxene and hornblende in plutonic and effusive rocks, and also upon the well-known fact that at high temperature and atmospheric pressure hornblende cannot exist, but when fused recrystallizes as pyroxene, and upon the experiments of von Chrustschoff,[2] who has obtained hornblende at a temperature of 550° C., with the presence of water, under which conditions a high pressure must be developed. However, attention should be called to the fact that his explanation does not take into account other important factors which certainly influence the crystallization of minerals, for example, the chemical composition of the magma, and the fusion point and specific gravity of the minerals.

Whatever the factors are which determine its crystallization, the fact is that hornblende began to crystallize in the place of pyroxene. The biotite appears to have been formed at this time with the hornblende. The production of the hornblende and biotite continued until the remaining magma had reached the composition of basic feldspar, which then crystallized and now forms the mesostasis. A zone of orthorhombic pyroxene succeeded by one of hornblende has been described as surrounding the olivine in this peridotite. The term "reaction-rims" has been applied to similar zones by various observers. It seems to me that this term is inapplicable to such zones. It is not probable that in such a case as this there is a reaction in a strict sense between the magma and the olivine. Moreover, the zones should not be compared to the "resorption-rims" found so commonly in certain effusive rocks, where, from the fusion of hornblende crystals, pyroxene has been produced. Such a zonal growth around the olivine seems to me comparable to the case described by Washington,[1] where colorless diopside phenocrysts are surrounded by a narrow border of yellowish-green augite, which corresponds to the small augites in the groundmass, or to those cases which are so common in plutonic rocks, even in this rock described, where hornblende is found surrounding the pyroxene.

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[1] Gesteine der Columbretes; Anhang: Einiges über die Beziehung von Pyroxen und Amphibol in den Gesteinen. By F. BECKE: Tsch. Mitt., Vol. 16, 1896, pp. 327–336.

[2] Bull. de l'Academie des Sciences, St. Petersburg, 1890, 13. Cf. BECKE, loc. cit., p. 337.

A general explanation which would account for the successive crystallization of pyroxene and hornblende in this rock should be applicable to such a zonal growth as occurs around the olivine, taking into consideration, of course, the probability that a factor of slight importance in the one case may be the controlling factor in the other. Such occurrences seem clearly to indicate a change in the chemical composition of the magma as the chief factor, but influenced more or less strongly by the pressure, the temperature, and also by other factors.

An analysis of this peridotite is given below:

ANALYSIS OF PERIDOTITE BY DR. H. N. STOKES.

SiO_2	44.99	MgO	21.02
TiO_2	.97	K_2O	.74
Al_2O_3	5.91	Na_2O	.91
Cr_2O_3	.25	H_2O 110°—	.63
Fe_2O_3	3.42	H_2O 110°+	3.19
FeO	8.30	P_2O_5	.05
MnO	trace	CO_2	trace (?)
NiO	none		
CaO	8.79		99.17

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[1] Italian Petrological Sketches, 4, The Rocca Monfina Region, by H. S. WASHINGTON, JOUR. GEOL., Vol. V, 1897, p. 254.

Chemical relations of the series.— In the preceding pages the mineralogical evidence has been given of the variations under discussion. In the following tables there are reproduced the analyses which have been given of the typical members of the different classes. They are arranged in order of diminishing acidity. In Table I the complete analyses are given.

I.

	1	2	3	4
SiO_2 - - - -	58.51	49.80	48.17	44.99
TiO_2 - - - -	.72	.79	1.00	.97
Al_2O_3 - - - -	16.32	19.96	25.26	5.91
Cr_2O_3 - -	none			.25
Fe_2O_3 - - - -	2.11	6.32	1.13	3.42
FeO - - - -	4.43	.49	6.10	8.30
MnO - - - -	trace	——[1]	——[1]	trace
NiO - - - -	none	——	——	none
CaO - - - -	3.92	11.33	9.53	8.79
MgO - - - -	3.73	7.05	4.22	21.02
K_2O - - - -	4.08	.61	.73	.74
Na_2O - - - -	3.11	2.22	1.34	.91
H_2O at 110° -	.23	100°— .13	100°— .19	110°— .63
H_2O above 110° -	2.00	100°+ 1.71	100°+ 2.00	110°+ 3.19
P_2O_5 - - - -	.30	.07	.07	.05
CO_2 - - - -	none	.15	.43	trace?
	99.46	100.63	100.17	99.17

II.

PERCENTAGES OF CHIEF OXIDES REDUCED TO 100.

	1	2	3	4
SiO_2 - - - -	60.36	49.80	49.41	47.33
TiO_2 - - - -	.75	.79	1.02	1.02
Al_2O_3 - - - -	16.83	19.96	25.96	6.22
Fe_2O_3 - - - -	2.17	6.32	1.16	3.60
FeO - - - -	4.57	.49	6.25	8.73
CaO - - - -	4.04	11.33	9.77	9.25
MgO - - - -	3.85	7.05	4.32	22.11
K_2O - - - -	4.21	.61	.74	.78
Na_2O - - - -	3.21	2.22	1.37	.96

[1] MnO, etc., not looked for.

III.

ATOMIC PROPORTIONS OF METALS.

Si	55.85	46.53	45.90	42.48
Ti	.53	.56	.72	.70
Al	18.41	22.03	28.50	6.60
Fe	5.08	4.83	5.70	9.02
Ca	4.04	11.42	9.79	8.98
Mg	5.32	9.85	6.01	29.67
K	4.99	.74	.89	.91
Na	5.78	4.04	2.49	1.67

In Table II there is given the percentages of chief oxides reduced to 100, and in Table III the atomic proportions of the metals.[1] The analyses show that all of the rocks contain a moderately large amount of water. Nevertheless, they are sufficiently well preserved to warrant a discussion of their analyses for classificatory purposes. Indeed, No. 4 is remarkably fresh for so basic a rock. With reference to analysis No. 1, it may be stated that the rock is, on the whole, one which it is somewhat difficult to place definitely in the existing division of rock families. The large amount of lime and relatively low percentage of alkalies prevent placing the rock with the syenites, which possibly the presence of the large amount of orthoclase might lead one to do if the rock were studied with the microscope alone. On the whole, it approaches close to the monzonites, according to their chemical composition as given by Brögger.[2] From this it differs, in that the lime, 3.92 per cent., is too low to bring the rock within his limits, 4.52 to 10.12 per cent. However, if we consider the total of the alkaline earths, 7.55 per cent., in this rock, we find that it comes well within Brögger's range, 6.05 to 17.52 per cent., for a total of magnesia and lime. Moreover, the alkali total, 7.19 per cent., is too high to warrant its classification in the monzonite class as a representative of the type of the biotite-monzonite.

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[1] These tables were calculated for me by MR. V. H. BASSETT, assistant in chemistry in the University of Wisconsin.

[2] Op. cit., Part II, p. 51.

On comparing the analysis with that of a normal diorite, we find the relative proportions of the alkalies are abnormal. Also the lime content is too low for rocks of this character; and, again, the magnesia is too high. From the above considerations it seems clear that the rock is related to the monzonites and diorites. However, it is so intimately associated with, and so evidently a facies of the tonalite, which is the dominant type where the mica-diorite occurs, that it is considered to be more closely related to the lime-soda-feldspar rocks in which the orthoclase is but accessory, than to the monzonite family of orthoclase-plagioclase rocks. It is, therefore, considered to be a mica-diorite. It has already been remarked that while for normal diorites the lime is too low, the magnesia is correspondingly too high. May we not with right consider this as indicating a relationship to the more basic rocks gabbros, in which magnesia forms a very important constituent and with which it is so intimately associated in the field? As against this interpretation, however, we have a very high percentage of alkalies and moderately high percentage of silica, which certainly warrant the exclusion of this rock from the gabbro family.

When we turn to a consideration of the gabbro-norites as represented by analyses Nos. 2 and 3, it is at once clear that if we accept, as has been done in the preceding pages, Brögger's[1] characterization of the diorite and gabbro families, that these rocks could not be included with the diorites as respectively normal diorite and bronzite-diorite, but must, from their abnormally low silica and alkali content and high alumina, lime, and magnesia content, be placed with the gabbros. Especially noteworthy in analysis No. 2 is the high percentage of alumina present. Normally, large alkali content accompanies high percentage of alumina. A reference to the alkalies shows this not to be true in this instance.

Analysis No. 4 is not to be taken as representing the most basic variety of peridotite in this district. From this alone the statement that the variations extend to the ultrabasic rocks would hardly be warranted. As has already been said, however, the rock of which the analysis was made is one which is feldspathic, and represents a transition upward into the gabbro.

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[1] Op. cit., Part II, pp. 35, 39.

Examining the series of analyses together, we see that in passing from the most acid to the basic end the alumina increases very rapidly to 25.96 per cent., until it reaches the extreme basic rock, when it drops suddenly to 6.22 per cent. The analyses also show an increase in the same direction in iron, as is best brought out in Table III. The alkalies increase with diminishing silica, whereas the magnesia, which for rocks of this character is very characteristic, shows a decided increase. In the gabbro-norite-peridotite portion of the series, analyses Nos. 2, 3, and 4, the lime shows a constant diminution, corresponding to the increasing magnesian character of the rocks. Likewise the potash increases as the soda diminishes. The rocks represented by the analyses are believed to belong to a series ranging from a diorite on the one hand through hornblende-gabbro and norite to a peridotite on the other. It is evident that a gap exists between the gabbro and diorite. The diorite represents a gradation towards the orthoclase rocks of essentially the same acidity. On this acid side of the series the microscope also shows variations to a tonalitic and even granitic rocks very rich in quartz and orthoclase, probably very much more acid in character than the diorite represented in the analyses.

Relations of the rocks of the series.—The rapid changes in mineralogical composition and texture in a single rock exposure, and the changes thus occasioned from one type into another through intermediate facies, show very clearly the intimate relationship of the Crystal Falls rocks to one another, and warrants the assumption that they all belong to a geological unit, a conclusion long since reached by Williams[1] for a similar group of rocks, "The Cortlandt Series" from New York. Variations very similar to those here described have been well described by Messrs. Dakyns and Teall from some Scottish plutonic rocks.[1] The field studies have shown the relations of the various members of this series from Crystal Falls to be as follows: The diorite is found cutting the hornblende-gabbro. The gabbro is also found to be cut by a dike of biotite-granite. The relation of this particular dike to the diorite could not be determined; therefore it has not been described. In one case, however, a dike cutting a gabbro showed biotite-granite as a facies of the diorite. It is probable that the other dikes of biotite-granite occurring in the area are facies of the same widely distributed diorite magma. The hornblende-gabbro is cut by the bronzite-norite and the peridotite. It is thus evident that the eruption of the hornblende-gabbro was followed by that of a peridotite on the one hand and by a diorite, possibly even a granite, on the other.

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[1] The peridotites of the "Cortlandt Series" on the Hudson River near Peekskill, N. Y., by G. H. WILLIAMS, Am. Jour. Sci., Vol. XXXI, 1886, pp. 26–41.

The norites of the "Cortlandt Series" on the Hudson River near Peekskill, N. Y., by G. H. WILLIAMS. Am. Jour. Sci., Vol. XXXIII, 1887, pp. 135–144, 191–199.

It is a difficult matter to estimate quantitatively the amount of the one or the other rock type present in the Crystal Falls district. We are thus prevented from drawing from the predominance of the one kind or the other the conclusion that those represented in the minority are the results of the differentiation of a magma most nearly resembling in its original constitution that which predominates. Moreover, since the analyzed rock types were not selected as representatives of the extremes of the process of differentiation, it would not be wise to endeavor to give the mean composition of the parent magma, from the analyses of the differentiation products which have been presented. The main thesis, however, seems to be established that the separation of a magma into the various products described has taken place, as is indicated by the relations in the field, and as has been shown by the microscopical and chemical analyses.

From the relations described as existing between the various

The gabbros and norites of the "Cortlandt Series" on the Hudson River near Peekskill, N. Y., by G. H. WILLIAMS, Am. Jour. Sci., Vol. XXXV, 1888, pp. 438–448.

[1] On the plutonic rocks of Garabal Hill and Meall Breac, by J. R. DAKYNS, ESQ., M.A., and J. J. H. TEALL, ESQ., M.A., F.R.S., F.G.S., Q. J. G. S., Vol. XLVIII, 1892, pp. 104–121.

kinds of rocks, it was seen that the hornblende-gabbro was unquestionably the one which first reached its present position. Whether this is to be regarded as itself representing the composition of the parent magma, or only as a differentiation product of a still deeper seated igneous mass, cannot of course be determined. Be that as it may, the fact, which has been proven, remains, that given the period of eruption of this hornblende-gabbro as a starting point, and possibly this magma as the original one, the forces of differentiation have been active in two directions, towards increasing acidity and increasing basicity, in agreement with the law of succession of igneous rocks as propounded by Iddings.[1]

J. MORGAN CLEMENTS.

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[1] The Origin of Igneous Rocks, by J. P. IDDINGS, Bull. Phil. Soc. Wash., Vol. XII, 1892, p. 145.

CORRECTED ANALYSIS.

There is given upon this sheet the corrected analysis of the bronzite-norite described upon page 382 of the May-June number of this Journal. The tables containing percentages of chief oxides, etc., have been calculated from this analysis, corresponding to those formerly given upon pages 387–8, and are also given here. It is requested that these analyses and tables be substituted in the places indicated by the table and page numbers which accompany them.

ANALYSIS OF BRONZITE-NORITE BY MR. GEORGE STEIGER.

Page 382.

SiO_2	48.23	Na_2O	1.34
TiO_2	1.00	H_2O 100 −	.26
Al_2O_3	18.26	H_2O 100 +	2.00
Fe_2O_3	1.26	P_2O_5	.07
FeO	6.10	CO_2	.43
CaO	9.39		——
MgO	10.84		99.91
K_2O	.73	MnO, etc., not looked for.	

Table I, page 387

	3
SiO_2	48.23
TiO_2	1.00
Al_2O_3	18.26
Cr_2O_3	
Fe_2O_3	1.26
FeO	6.10
MnO	——
NiO	——
CaO	9.39
MgO	10.84
K_2O	.73
Na_2O	1.34
H_2O 100−	.26
H_2O 100+	2.00
P_2O_5	.07
CO_2	.43
	99.91

Table II, page 387

	3
SiO_2	49.64
TiO_2	1.03
Al_2O_3	18.79
Fe_2O_3	1.30
FeO	6.28
CaO	9.67
MgO	11.16
K_2O	.75
Na_2O	1.38

Table III, page 388

	3
Si	45.27
Ti	.71
Al	20.26
Fe	5.70
Ca	9.51
Mg	15.22
K	.88
Na	2.45